

# **An Expert System for Marine Environmental Monitoring in the Florida Keys National Marine Sanctuary and Florida Bay\***

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## **Abstract**

The National Oceanic and Atmospheric Administration's (NOAA, U.S. Department of Commerce) Atlantic Oceanographic and Meteorological Laboratory (AOML) works cooperatively with the Florida Institute of Oceanography (FIO) in the implementation of the SEAKEYS (Sustained Ecological Research Related to Management of the Florida Keys Seascape) network, which is situated along 220 miles of coral reef tract within the Florida Keys National Marine Sanctuary (FKNMS). This network is itself actually an enhanced framework of seven Coastal-Marine Automated Network (C-MAN) stations for long-term monitoring of meteorological parameters (wind speed, wind gusts, air temperature, barometric pressure, relative humidity). To the C-MAN network SEAKEYS adds oceanographic parameters (sea temperature, photosynthetically active radiation, salinity, fluorometry, optical density) to the stations. As a recent enhancement to the SEAKEYS network, an expert system shell is being employed to provide daily interpretations of near real-time acquired data for the benefit of scientists, fishermen and skin divers. These interpretations are designed to be automatically emailed to Sanctuary managers and to the FIO maintainers of the network. The first set of interpretations include those dealing with environmental conditions conducive to coral bleaching. Other marine environmental interpretations are slated to follow.

## **1 Introduction**

### **1.1 Background**

The Florida Keys National Marine Sanctuary (FKNMS) was established to provide protection for a unique marine ecosystem in the Florida Keys so that generations of visitors could enjoy the beauty of coral reefs and the enjoyment of water sports such as skin and scuba diving, boating and fishing. "Protection" entails not only the policing of the Sanctuary to prevent plundering of its natural resources by poachers, but also monitoring the status (i.e., "health") of the ecosystem so that appropriate steps may be taken in the event anthropogenic stressors threaten the environment. The FKNMS also seeks to support basic research of the marine ecosystem to further understand its mysteries, and, where applicable, to apply the findings of that research not only to the general fund of knowledge, but toward greater enjoyment for its visitors. Conservation and understanding of the Florida Keys natural marine resources are its prime directives.

At the National Oceanic and Atmospheric Administration's (NOAA) Atlantic Oceanographic and Meteorological Laboratory (AOML), Ocean Chemistry Division (OCD), in Miami, Florida, environmental data such as wind speed, barometric pressure, dew point, sea temperature and salinity are acquired from

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remote sites on lighthouses and navigational aids situated at reefs along and within the FKNMS via a satellite data archival site at Wallups Island, Virginia. The data are collected at the sites hourly by oceanographic instruments which are maintained by the Florida Institute of Oceanography (FIO) and meteorological instruments which are maintained by the National Data Buoy Center (NDBC) of NOAA. There are currently six sites, which have been termed the SEAKEYS (Sustained Ecological Research Related to Management of the Florida Keys Seascape; Ogden [1]) network: Fowey Rocks (in Biscayne National Park), Molasses Reef (off Key Largo), southern Florida Bay (off Long Key), Sombrero Key (off Marathon), Sand Key (near Key West), Dry Tortugas, and northwestern Florida Bay. Field maintenance for the oceanographic instruments, and data management for these sites, are being funded by NOAA's South Florida Ecosystem Restoration, Prediction and Modeling (SFERPM) program, which seeks to describe, model, predict and, where indicated, restore marine and coastal ecosystem processes in and near Florida Bay. The SFERPM program has extended the existing monitoring capabilities of the SEAKEYS network by funding the addition of instruments for measuring turbidity, fluorometry and water level at three sites critical to the interaction of Florida Bay and the FKNMS.

There are many physical, chemical and biological events of interest and concern to the managers of the FKNMS, marine biologists, oceanographers, fishermen and divers. Some of these events would of course be observable if it were possible to continuously be present at a remote site of interest, or if instrumentation could monitor the remote site and the observer could in turn monitor the output of the instrumentation. Except in very critical cases, however, the truth is that large volumes of data are generated by instruments which may be distributed over many sites (as in the SEAKEYS network), and no one has the time to look at every printout of data from every station, every day, seven days a week. It is highly desirable to have an automated system that can monitor meteorological and oceanographic parameters and produce specialized alerts of specific events. The expert system described here collects data from one station (Sombrero Key) in the SEAKEYS network and produces automated email and World-Wide Web (the "Web") alerts when conditions are conducive to coral bleaching. This represents the first of many applications for this system.

## **1.2 Expert Systems**

Expert systems, or knowledge-based systems, are a branch of artificial intelligence. Artificial intelligence is the capability of a device such as a computer to perform tasks that would be considered intelligent if they were performed by a human (Mockler & Dologite [2]). An expert system is a computer program that attempts to replicate the reasoning processes of experts and can make decisions and recommendations, or perform tasks, based on user input. Knowledge engineers construct expert systems in cooperation with problem domain experts so that the expert's knowledge is available when the expert might not be, and so that the knowledge can be available at all times and in many places, as necessary. Expert systems derive their input for decision making from prompts at the user interface, or from data files stored on the computer. The knowledge base upon which the input is matched is generally represented by a series of IF/THEN statements, called production rules, which are written with the domain expert to approximate the expert's reasoning. The degree of belief the expert has in her conclusion is represented as a confidence factor (CF) in the expert system. For instance, the expert may feel that the conclusion based upon the input has a 95% probability of being correct, so the CF would equal 95.

## **1.3 Expert Systems in Oceanography**

There appear to have been relatively few expert systems constructed, or envisioned, for oceanographic and maritime purposes. Ryan and Smith [3] proposed an expert system for fisheries management purposes; however, the senior author developed interests elsewhere and the project idea was dropped (P. Smith, personal communication). Holland [4] proposed the use of an expert system and other artificial intelligence tools for the extraction of marine environmental information, but apparently was never able to follow up with funding to develop a system. Sigillito et al [5] and Wachter and Sigillito [6] developed a prototype system, XCOR, to aid human analysts in detecting and correcting errors in oceanographic data collected from research and merchant voluntary observing ships throughout the world. Groundwater [7] developed a preliminary "ocean surveillance information fusion expert system" which modelled the thought processes of a surveillance watch analyst who assesses vessels' missions and destinations given

their previous record of tracks, history and locations/status of other vessels in a particular domain of interest (e.g., shipping). Lybanon and associates [8, 9, 10, 11] developed a successful expert system for the interpretation of image data for the purpose of predicting movements of the Gulf Stream, as did Thomason [12]. Dantzler and Scheerer [13] and Scheerer and Dantzler [14] apparently spent a considerable amount of time and effort in the design of an expert system for predicting the coastal ocean environment. However, these authors eventually split their efforts along different lines to develop the Tactical Oceanographic Monitoring System [15], which does not appear to use an expert system framework, and explorations into the relationship between upwelling and fog formation using sea surface temperatures and the Regional Atmospheric Modeling System (D. Scheerer, personal communication). Cochrane and Hutchings [16] suggested that an expert system could be developed for forecasting recruitment of anchovies, using observed values of copepod biomass and oocyte development in adult female anchovies, but the system has yet to be developed. Hendee [17] constructed an expert system to determine whether oceanographic data collected at sea represented reasonable values as compared to those collected by other ships at sea visiting the same area.

## **1.4 Coral Bleaching**

Coral bleaching may be described as the general whitening of coral tissues due to the release of symbiotic zooxanthellae and/or reduction in photosynthetic pigment concentrations in the zooxanthellae residing within the tissues of the host coral (Glynn [18]). Bleaching can be a generalized stress response to harsh environmental conditions such as high sea temperature or abnormal salinity (abiotic-induced bleaching), bacteriological or viral infection (biotic-induced bleaching), or for other unknown reasons (Glynn [18], Kushmaro et al [19]). In most reported incidences of coral bleaching, however, high sea temperature is in evidence and appears to be the chief environmental stressor [Brown & Ogden [21], whether those temperatures may be considered “abnormal” or not (see, for example, Atwood [23]). One other event that appears to influence abiotic-induced bleaching is the presence of low wind speed, as this apparently favors localized heating and a greater penetration of solar radiation (Glynn [18]; Causey [22]; Jaap [23]; Lang [24]). The expert system described below screens near real-time incoming wind speed, sea temperature and photosynthetically active radiation (PAR) data to determine if conditions are optimal for abiotic-induced coral bleaching at Sombrero Key. The use of the expert system allows researchers to model the environment to further understand the phenomenon, as the knowledge base can be easily reconfigured. The automated transmittal of the bleaching alerts also gives the FKNMS managers some immediate feedback on one facet of the “health” of the sanctuary. It similarly alerts researchers so that they may travel to the site for further study, and so that they may provide feedback to the knowledge engineer for further fine-tuning of the system (e.g., whether or not bleaching is beginning to occur or not). Finally, development of the framework for monitoring and reporting provides a springboard for other environmental modeling, for example, harmful algal blooms (i.e., “red tide”).

# **2 Methods**

## **2.1 Expert System Development**

CLIPS (C Language Integrated Production System) was used for the expert system shell, and Hypertext Markup Language was used for the presentation of data and expert system analyses via the Web. The expert system proceeds in different stages.

### **2.1.1 Stage 1**

Every day at 4:05 am, an automated data acquisition program is initiated. The program uses communications software and a modem to call a location at Wallups Island, Virginia, which holds the archived raw data. The data held are those which were collected five minutes earlier via a satellite from the SEAKEYS stations in the FKNMS, which transmit the data on the hour, every hour. From the archived site, a caller can acquire data for the last 72 hours worth of transmissions from the stations. After the program makes contact with the archival site, using a password, a special prearranged data suite identifier is supplied. The required data are then supplied to the screen, and the program captures the whole session in a file. The data represent values recorded from instruments designed to measure barometric pressure,

wind speed, wind gusts, wind direction, air temperature, sea temperature, salinity, photosynthetically active radiation (PAR), and sensor depth, which provides an indirect measurement of the state of the tide. With these data are also sent the station name, date and time (GMT).

The raw data file captured by the data acquisition module is parsed to extract the data of interest. The data are written to an ASCII text file in a format that can be read and interpreted by Stage 2, described below. This file is more easy to work with than the complex raw file. CLIPS is used as the data parser, as programming language classes for each SEAKEYS station are the same, and code changes due to data stream changes at each station are more easy to effect without having to recompile an executable, as in a language like C. Also, program code is easily portable across operating systems when using CLIPS.

### 2.1.2 Stage 2

ASCII data files produced in Stage 1 are screened against production rules to determine whether the values for the instruments are within realistic ranges, or whether the instrument appears to be malfunctioning or offline (garbled or no data). To aid in the analysis of data, which may vary widely depending upon the time of day and the season of the year, values are averaged for eight three-hour periods per day, termed midnight (2200 to 0100 hours local time), pre-dawn (0100 to 0400 hours), dawn (0400 to 0700), morning (0700 to 1000 hours), all day (1000 to 1300), pre-sunset (1300 to 1600), and evening (1900 to 2200 hours). These groupings are convenient because meteorological phenomena quite often show predictable fluctuations during these periods of the day, for instance the change of wind direction and wind speed with sunrise and sunset. The averaged values within each of these categories are then determined to fall within one of eleven categories: unbelievably low, drastically low, very low, low, somewhat low, average, somewhat high, high, very high, drastically high, and unbelievably high. These groupings are arbitrary names, of course, and parameters such as wind direction are further translated to different regions of the compass (e.g., NE-ENE). The assignment of values to these categories depends upon what the season of year is (spring, summer, fall or winter), so, for instance, what might be considered “somewhat high” in winter might otherwise be considered to be “average” during summer. Values which are determined to be “unbelievably high” or “unbelievably low” represent values which are considered to be totally unrealistic for the parameter in question. However, should it happen that these values begin to represent real-life values, the ranges may be easily reset to encompass the newer values.

The instruments themselves are visited once a week by field technicians of the FIO so corrective maintenance of the oceanographic sensors can be attended to as necessary. In any case, oceanographic instruments become fouled and must be cleaned periodically. Sea temperature and salinity sensors are “sea-truthed” during the station visits. That is, calibrated instruments are taken into the field and measured at the same time the *in situ* instruments make their automated measurements to see if the *in situ* instrument needs to be replaced, or its data need to be corrected. Meteorological instruments are maintained by NDBC. If any of the instruments are malfunctioning, the expert system code is easily adjusted so that those values are not accounted for in the process. Under Stage 3 (below), production rules requiring measurements from the malfunctioning instrument simply do not fire, but the fact of a malfunctioning instrument is sent via email and saved as a file for that day’s worth of data interpretations.

The status of the parameters, that is, where they are on the continuum from unbelievably low to unbelievably high, and when these values occurred (i.e., the period of the day), are saved as “facts” in a text file, which is loaded into the program under Stage 3 processing.

### 2.1.3 Stage 3

The “facts” loaded from the processing under Stage 2 (which requires about 1800 production rules) represent subjective interpretations of the measured data, and therefore represent *information*, not just columns of numbers. This information synthesis, proceeding according to how experts view the ranges of data, makes the further processing for the benefit of determining environmental trends and events easier in the context of an expert system. At this point, information represented as occurring through time (since the “facts” show data progress through the previous 72 hours, or longer still, if desired), presents an enormous range of possibilities for further processing, limited only by the skill of the programmer and the time required for coding.

There is an excellent chance that abiotic-induced coral bleaching can be predicted, as this appears to be a function of environmental stress. As mentioned above, high sea temperature alone, or in combination with low wind speeds and/or high solar radiation appear to be the chief stressors involved, whether they are the sole causative agents or not. The following pseudocode represents one of the production rules of the coral bleaching module of this expert system:

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IF sea temperature is drastically high all day,  
AND wind speed is very low all day,  
AND wind gusts are very low all day,  
AND PAR at 1 m is drastically high during daylight hours,  
THEN there is a high probability (CF = 95) that  
    abiotic-induced coral bleaching will occur.
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Additional production rules make CF assertions depending upon the subjective values of all the variables. If a parameter is missing because an instrument is malfunctioning, rules fire which do not depend on the parameter in question; thus, the CF would be lower.

As the model proves to be right or wrong, using feedback from sanctuary divers, the knowledge base is adjusted to more accurately predict further bleaching events, and researchers begin to further understand the phenomenon.

### 3 Results

In a test of the system, data from 1997 during the time of widespread coral bleaching at Sombrero Key, were used as input, however values for PAR came from another station, as the Sombrero Key station did not have operable PAR sensors at that time. Unfortunately, data were not kept during summer 1997 as to the first occurrence of coral bleaching, so more refined testing of the ability of the system to predict bleaching could not be done. However, the real values and fabricated values resulted in the system correctly detecting and reporting conditions that would be expected to be conducive to coral bleaching. The expert system continues to execute every morning after receipt of the daily data, so it is anticipated that the first alerts may come this summer, if the conditions occur again. These alerts will be available via the Web at <http://coral.aoml.noaa.gov/sferpm/seakeys/es>. NOAA and FIO divers will be alert to the first signs of coral bleaching at Sombrero Key, and will offer feedback on the further development of the system.

At this time, less refined output of the system, available at the same Web address, reflects the status of the last seven days of processed data for all parameters. This portion of the system still requires much work.

### 4 Discussion

It is anticipated that further development of the expert system described here might provide alerts such as conditions conducive to the onset of harmful algal blooms (e.g., "red tide"), conditions conducive to the arrival of commercially important fisheries stocks (such as pink shrimp, *Penaeus duorarum*), conditions conducive to larval fish (and other animal) survival or death (e.g., extended high or low temperatures), incidences of extended duration of clear or turbid water (via optical density measurements), phytoplankton blooms (measured directly through fluorescence), influx of hypo- or hypersaline waters from Florida Bay through the Florida Straits, excessive dissolved nutrient encroachment (reflected in sustained high levels of fluorescence), and the influx of cool or warm water from Florida Bay through the Florida Straits. Such predictive models, through iterative development with domain experts, will help environmental managers and scientists understand natural cycles in Florida Bay, and serve as a backdrop for feedback on, and development of, environmental regulations.

## 5 References

- [1] Ogden, J., Porter, J., Smith, N., Szmant, A., Jaap, W. & Forcucci, D. A long-term interdisciplinary study of the Florida Keys seascape. *Bulletin of Marine Science*, **54(3)**, 1059-1071, 1994.
- [2] Mockler, R.J. & Dologite, D.G., *Knowledge-Based Systems. An Introduction to Expert Systems*, Macmillan Publishing, New York, 1992.
- [3] Ryan, J.D & Smith, P.E., An “expert system” for fisheries management. *Oceans '85 Proceedings: Ocean Engineering And The Environment*, **2**, pp. 1114-1117, 1985.
- [4] Holland, C.R., Artificial intelligence and the extraction of marine environmental information. *Proceedings Marine Data Systems '86: Marine Data Systems International Symposium*, pp. 433-436, 1986.
- [5] Sigillito, V., Wachter, R. & Hunt, R., Jr., XCOR—A knowledge-based system for correction of oceanographic reports. *IEEE Symposium: Expert Systems in Government* [Proceedings held in McLean, VA, October 24-25. Available from IEEE Service Center (Cat no. 85CH2225-1), Piscataway, NJ.], pp. 190-195, 1985.
- [6] Wachter, R.F. & Sigillito, R.G. Man-machine interface for a knowledge based system for validating oceanographic reports. *Second Conference on Artificial Intelligence Applications: The Engineering of Knowledge-Based Systems*, [Available from IEEE Service Center (Cat no. 85CH2215-2), Piscataway, NJ], pp. 342-346, 1985.
- [7] Groundwater, E.H., An expert system for ocean surveillance. *IEEE Symposium: Expert Systems in Government* [Proceedings held in McLean, VA, October 24-25. Available from IEEE Service Center (Cat no. 85CH2225-1), Piscataway, NJ.], pp. 196-199, 1985.
- [8] Bridges, S.; Chen, L-C & Lybanon, M., Predicting and explaining the movement of mesoscale oceanographic features using CLIPS. *Proceedings 3rd Conference on CLIPS, September 12-14, 1994. LBJ Space Center*, p. 211-216, 1994.
- [9] Romalewski, R.S. & Lybanon, M., Implementation of an oceanographic expert system: Problems, feedback, solutions. *NOARL-PR-89-069-252*, [Available from: Naval Oceanographic and Atmospheric Research Lab., Stennis Space Center, MS], 6 pp. ,1990.
- [10] Lybanon, M. & Romalewski, R., An expert system to aid the oceanographic image analyst. *SPIE 1293, Applications of Artificial Intelligence VIII*, 918-928, 1990.
- [11] Lybanon, M., McKendrick, J., Blake, R., Cockett, J. & Thomason, M.G., A prototype knowledge-based system to aid the oceanographic image analyst. *SPIE 635, Applications of Artificial Intelligence III*, 203-205, 1986.
- [12] Thomason, M.G., *Oceanographic expert system development: Final report—Year 1*. Knoxville, TN: Perceptronics Corporation. [NTIS Order No.: AD-A189 134/0/GAR. Contract N00014-87-C-6001], 1987.
- [13] Dantzler, H.L. & Scheerer, D.J., An expert system for describing and predicting the coastal ocean environment. *Johns Hopkins APL Technical Digest*, **14(2)**, 181-192, 1993.
- [14] Scheerer, D.J. & Dantzler, H.L., Jr., Expert system tools for describing and predicting the coastal ocean environment. *IEEE Ocean* **2(II)**, 11-16, 1994.

- [15] Dantzler, H.L., Jr., Sides, D.J. & Neal, J.C., An automated tactical oceanographic monitoring system. *Johns Hopkins APL Technical Digest* **14(3)**, 281-295, 1993.
- [16] Cochrane, K.L. & Hutchings, L., A structured approach to using biological and environmental parameters to forecast anchovy recruitment. *Fisheries Oceanography* **4(2)**, 102-127, 1995.
- [17] Hendee, J., PELAGOS: An expert system for quality control and feature recognition of oceanographic data from the open ocean. *National Oceanic and Atmospheric Administration, Technical Memorandum, Environmental Research Laboratories, AOML-87*, 1995.
- [18] Glynn, P., Coral reef bleaching: ecological perspectives. *Coral Reefs* **12**, pp 1-17, 1993.
- [19] Kushmaro, A., Rosenberg, E., Fine, M. & Loya, Y., Bleaching of the coral *Oculina patagonica* by *Vibrio* K-1. *Marine Ecology Progress Series* **147(1-3)**, pp. 159-165, 1997.
- [20] Brown, B.E & Ogden, J.C., Coral bleaching. *Scientific American*, **268**, pp. 64-70, 1993.
- [21] Atwood, D.K., Hendee, J.C., Mendez, A., An assessment of global warming stress on Caribbean coral reef ecosystems. *Bulletin of Marine Science*, **51(1)**, pp. 118-130, 1992.
- [22] Causey, B.D., Observations of environmental conditions preceding the coral bleaching event of 1987—Looe Key National Marine Sanctuary. *Proceedings Association of Island Marine Laboratories of the Caribbean*, **21**, pp. 48, 1988.
- [23] Jaap, W.C., The 1987 zooxanthellae expulsion event at Florida reefs. *NOAA's Undersea Research Program Research Report* **88(2)**, pp. 24-29, 1988.
- [24] Lang, J.C., Apparent differences in bleaching responses by zooxanthellate cnidarians on Colombian and Bahamian reefs. *NOAA's Undersea Research Program Research Report* **88(2)**, pp. 30-32.